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Recent Developments in Refractive Concentrators for Space Photovoltaic Power Systems

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Since SPRAT XI, significant progress has been made in the development of refractive concentrator elements and components designed specifically for space applications. This paper will discuss the status of the mini-dome Fresnel lens concentrator array and then summarize the results of work recently completed in the area of prismatic cell covers for concentrator systems. This will be followed by a brief discussion of some work just starting in the area of line-focus refractive concentrators for space.

INTRODUCTION

Since 1986 NASA Lewis and ENTECH, Inc. have been working on developing high efficiency, light weight refractive concentrator optics and components for use with space photovoltaic (PV) power systems. Since that time, considerable progress has been made in the development of the mini-dome Fresnel lens photovoltaic concentrator system (refs. 1,2). Within the past year, a number of new developments have been made, particularly in the area of prismatic cell covers. This paper will address four main areas:

1. Mini-Dome Fresnel Lens Concentrators
2. All-Glass Prismatic Cell Covers
3. Silicone Prismatic Cell Covers
4. Line-Focus Fresnel Lens Concentrators

The first area will cover the current status of the mini-dome concentrator program, which has been the focus of NASA's photovoltaic concentrator program over the past number of years. The next two areas will discuss new developments in the area of prismatic cell covers for both space and terrestrial applications. As will be discussed further, the new developments in terrestrial-based silicone prismatic cell cover technology could have a significant impact on the manufacturability and cost of future space refractive concentrator systems. The last topic will address the development of a linear refractive concentrator element under a program that has just started.

MINI-DOME FRESNEL LENS CONCENTRATORS

The mini-dome Fresnel lens concentrator is a unique point-focus refractive concentrator lens that was originally developed under the NASA and SDIO Small Business Innovation Research (SBIR) Programs by ENTECH, Inc.

Since 1989 the Boeing High Tech Center and the Boeing Defense & Space Group have pursued the development of this technology, expending a considerable amount of resources to bring this technology from a conceptual design and prototype component hardware stage to a point where the feasibility of assembling manufacturable concentrator array modules into a high efficiency, light weight power system has been demonstrated. These developments, along with a more detailed description of the hardware, have been discussed in previous papers (refs. 2,3) and will not be reviewed at this point.

Currently, the mini-dome concentrator program, both within NASA Lewis and at Boeing, emphasizes the large-scale manufacturability and assembly of array components as well as environmental and performance testing at the component and module level. The thermal cycling of various tandem cell interconnect patterns and prototype modules (ref. 4) has been performed. There are also a number of shuttle-based flight experiments planned that will evaluate the environmental stability of lens materials. Lens and cell material samples were recently flown on the EOIM-3 shuttle experiment. The results from this experiment are currently being analyzed will be reported once the post-flight data analysis is complete.

The key experiment for the mini-dome technology at this point is the Photovoltaic Array Space Power Plus Diagnostics (PASP Plus) Flight Experiment. PASP Plus is an Air Force-sponsored experiment that will test twelve different types of photovoltaic cell/array configurations in space (ref. 5). The Pegasus-launched experiment will have a highly elliptical orbit (190 n.m. by 1050 n.m., 70 degree inclination) that will expose the test modules to a variety of space environmental conditions (radiation, atomic oxygen, space plasma, etc.). An important feature of the PASP Plus experiment is that a number of the test modules will be biased to voltages up to ± 500 V in order to investigate array interaction with the space plasma under simulated high voltage array operating conditions.

One of the twelve individual experiments on PASP Plus is a NASA Lewis/Boeing mini-dome Fresnel lens concentrator module. The experimental module, built by Boeing, is 7.5 by 4.4 inches in size and consists of 12 lens-cell elements. A photograph of the flight hardware is shown in Figure 1. The concentrator lenses are made from silicone (DC 93500) and coated with a proprietary coating for protection against atomic oxygen and UV degradation. The cells are gallium arsenide/gallium antimonide (GaAs/GaSb) tandem cells made by Boeing. Each cell operates under a concentration of approximately 50 suns and has a pointing requirement of ± 2 degrees.

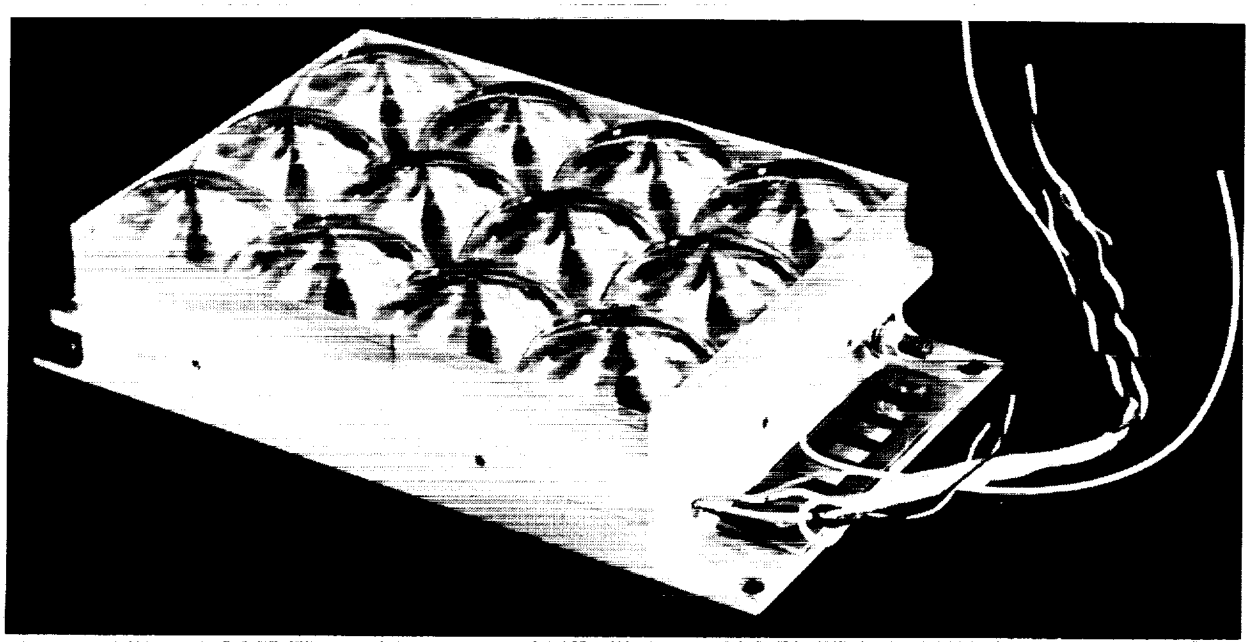


Figure 1. Photo of the mini-dome Fresnel lens concentrator test module being flown on the Photovoltaic Array Space Power Plus Diagnostics (PASP Plus) Flight Experiment.

Each set of three tandem cells is wired in a triplet configuration (ref. 6) which consists of three GaAs cells each in parallel with a series string of three GaSb cells. The four triplets are then wired in series to provide a two terminal output for the test module.

The PASP Plus experiment will be the first space flight test of the mini-dome concentrator lens and GaAs/GaSb cell technologies. In addition to the normal performance and long-term stability test data expected from this experiment, the mini-dome concentrator module will also participate in the high voltage plasma interaction part of PASP Plus. Ground-based testing on an earlier prototype module has shown minimal interaction with the space plasma at voltages up to $\pm$ 500 V. It is anticipated that the flight data from PASP Plus will confirm the expectation, based on previous ground-based testing, that concentrator arrays are less susceptible to plasma interaction effects than normal planar arrays at high operating voltages. This is due primarily to the inherent shielding of the cell from the space plasma that is provided by the concentrator array structure. The scheduled launch date for the PASP Plus experiment is the summer of 1993, with an expected operational lifetime of from 1 to 3 years.

ALL-GLASS PRISMATIC CELL COVERS

The concept of the prismatic cell cover has been around for a number of years. Projected applications have ranged from use on cells in planar arrays to ENTECH's patented concept of using the prismatic cover in conjunction with a concentrator element. The basic concept of the prismatic cell cover is shown in Figure 2. Utilizing the refractive optics of the prism cover, light is redirected away from the top metal gridlines toward the active area of the cell below. This translates into an increase in the amount of current produced by the cell and, if properly designed, is directly proportional to the amount of metallization covering the front surface.

ENTECH has had considerable experience using prismatic covers on their terrestrial concentrator systems. These prism covers are made from silicone. While silicone materials have been used extensively in space, specifically as an adhesive for bonding coverglasses to photovoltaic cells, there are a number of anticipated applications where all-glass prism covers would be desirable.

For space applications, a glass prismatic cell cover has a number of advantages. Glass is resistant to ultraviolet radiation, impermeable to monatomic oxygen, and provides excellent and well known resistance to particulate radiation. In addition, glass is very stable, even at extremely high temperatures. Thus if a glass prismatic cover were electrostatically bonded to a solar cell, the cell assembly could tolerate extremely high temperatures. Unfortunately, glass is very difficult, if not impossible, to form into the intricate prismatic cover shape with normal glass-forming technology. Under Phase I of an SDIO-sponsored SBIR contract, ENTECH and GELTECH, Inc., a small company with significant experience in forming small, high quality glass products, have successfully developed an all-glass prismatic cover via the sol-gel casting process (ref. 7). In sol-gel processing, very small colloidal particles are first formed in a solution. In sufficient concentration, these very small particles link together in chains, and then, in turn, into three-dimensional networks. Using a multi-step processing sequence, the gels can be molded exactly or very close to a final desired shape. The characteristics and properties of the pure silica made by sol-gel technology are equal to or better than those of other commercially available silicas.

A schematic of the prototype cover produced under the SBIR contract is shown in Figure 3. To cast the silica prismatic cell covers using the sol-gel process, a polystyrene mold was used. Polystyrene was selected as the best material for making the expendable molds due to its known compatibility with the sol-gel material and the casting process. The polystyrene molds were made from an existing diamond-cut master prism cover tool which was available to ENTECH.

An important point to note is that during sol-gel processing an enormous amount of shrinkage takes place. Shrinkage in all three dimensions must be accounted for when designing the sol-gel casting mold in order to achieve a final part with the desired dimensions. Despite the enormous amount of shrinkage inherent in the sol-gel process (equivalent to a 94% reduction in volume), the replication accuracy was outstanding. Figures 4 and 5 are photographs of the polystyrene mold and the silica prism cover respectively. (Note that the change in the magnification in the two photographs is due to shrinkage of the silica part after sol-gel processing). To further

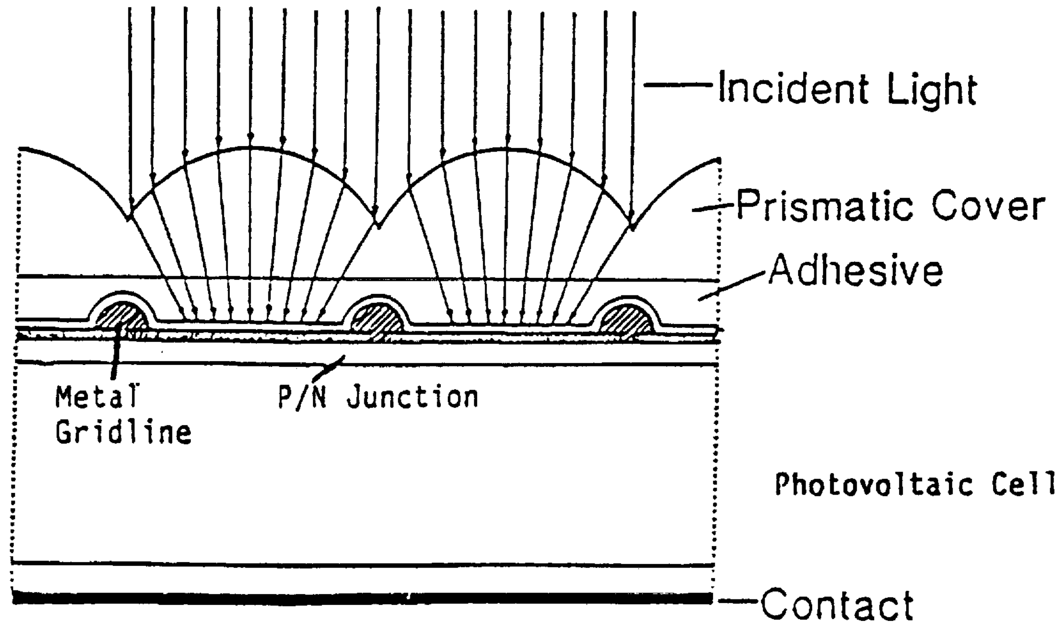
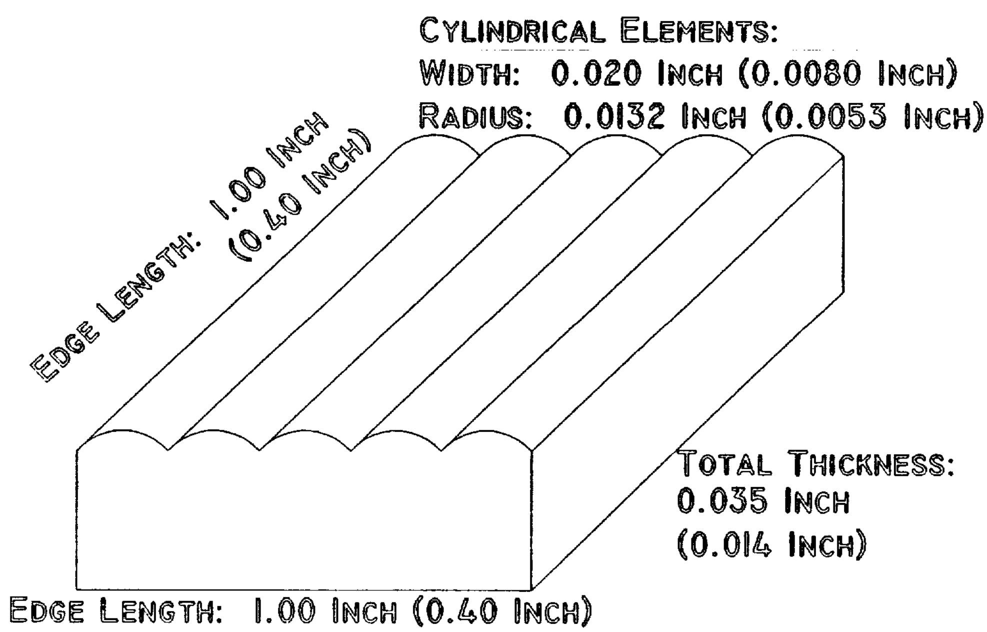


Figure 2. Cross-section of ENTECH's patented prismatic cell cover.



NOTE: INITIAL (MOLD) DIMENSIONS WITHOUT PARENTHESES
FINAL (PART) DIMENSIONS AFTER SHRINKAGE SHOWN IN PARENTHESES

Figure 3. Schematic of selected sol-gel prismatic cell cover design. (Optical elements greatly exaggerated in size. Only 5 elements of the 50 elements are shown.)

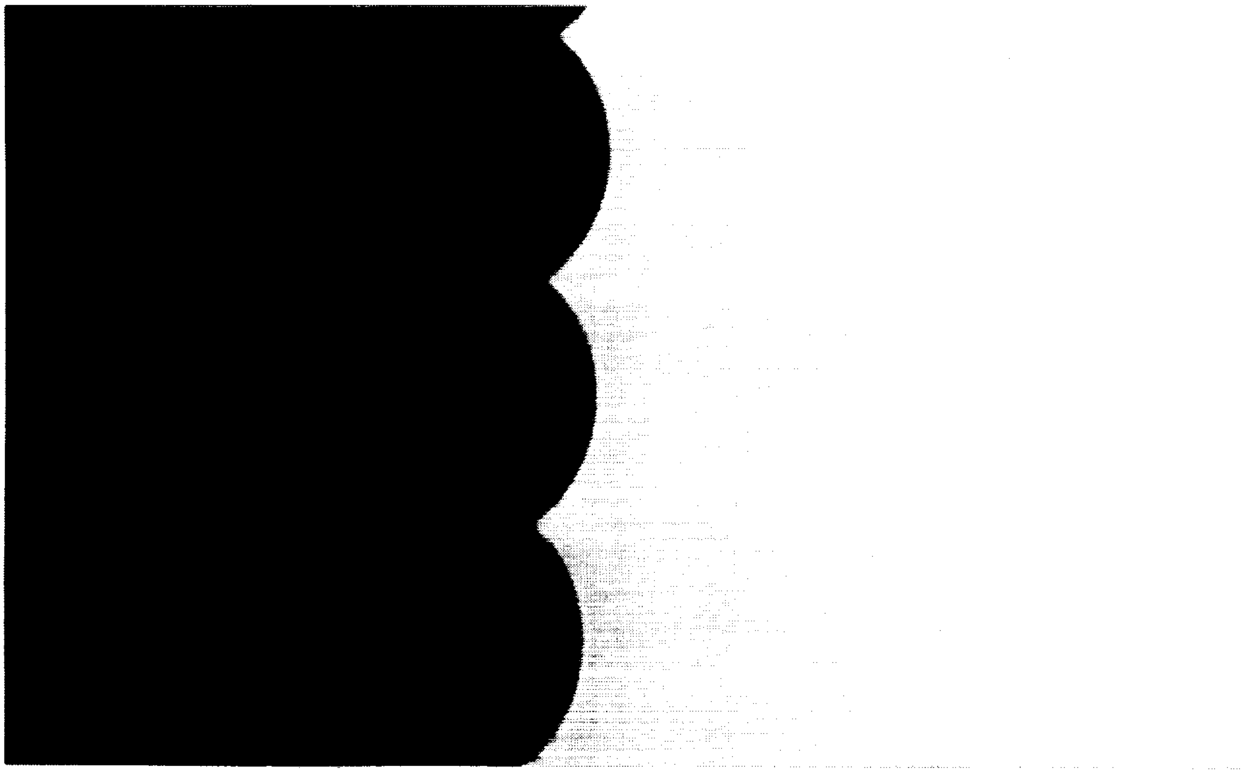


Figure 4. Silicone rubber impression of polystyrene mold at 50X magnification. (White color on right represents polystyrene mold cross-section).

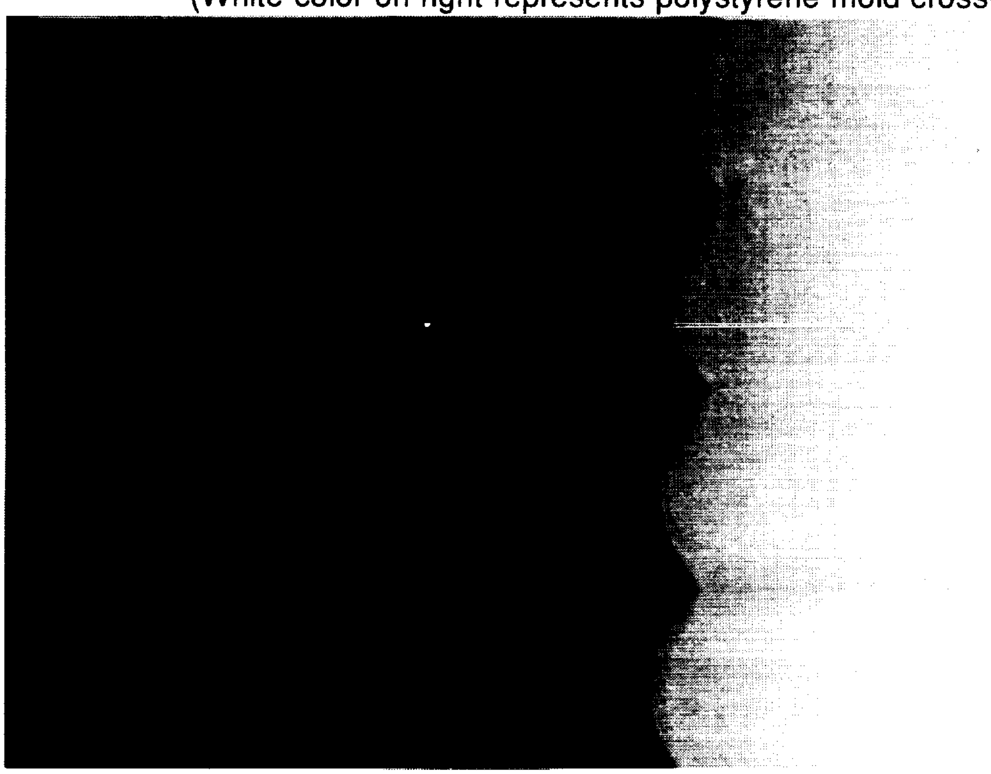


Figure 5. Silicone rubber impression of prismatic cell cover at 100X magnification. (White color on right represents silica cell cover cross-section).

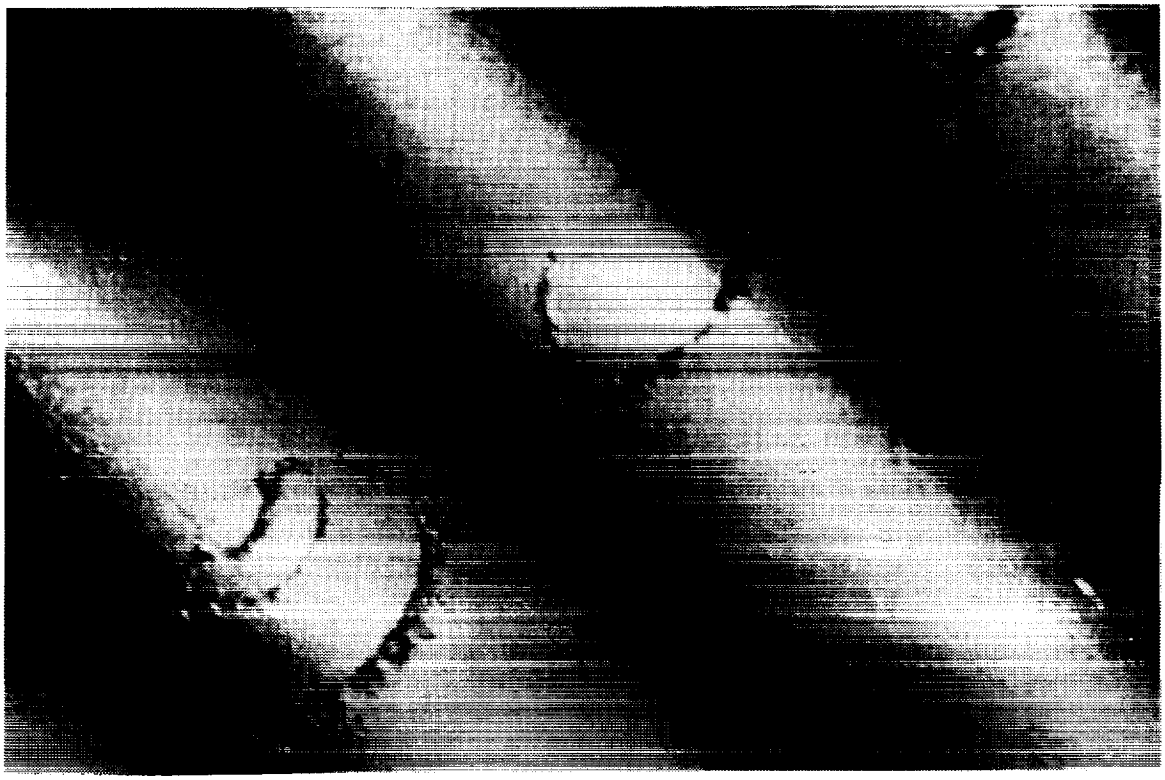


Figure 6. Polystyrene mold surface at 100X magnification.

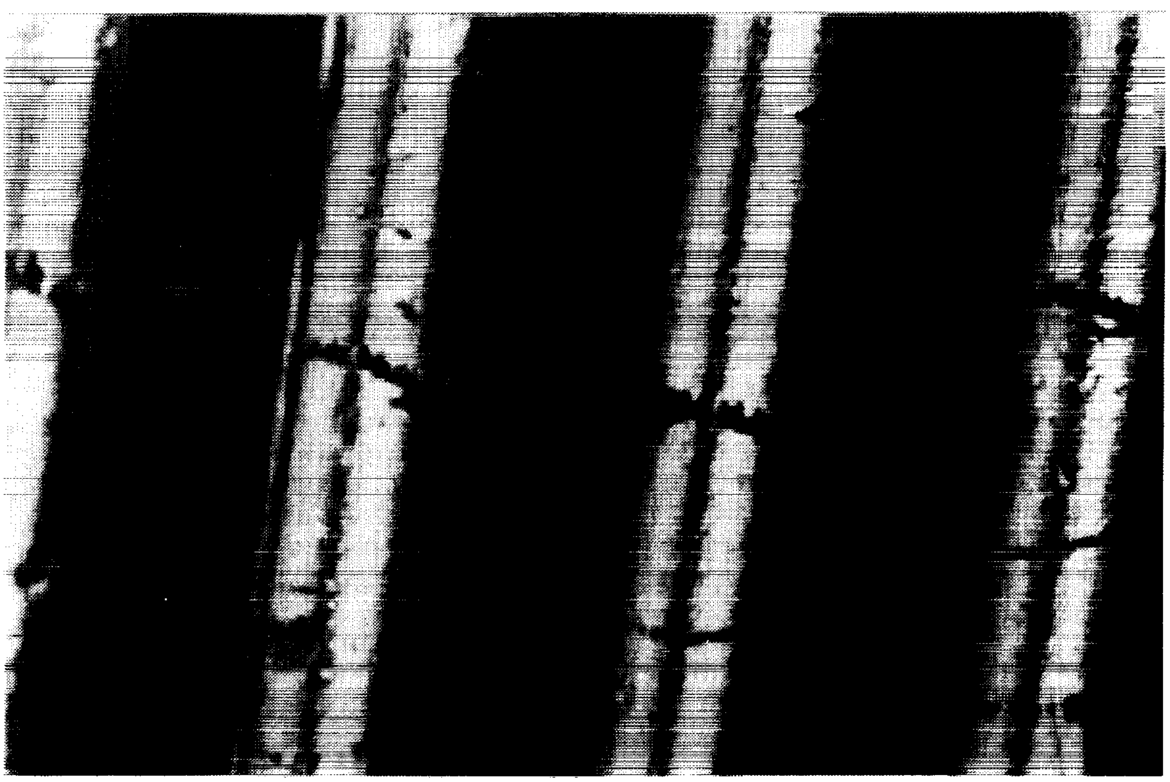
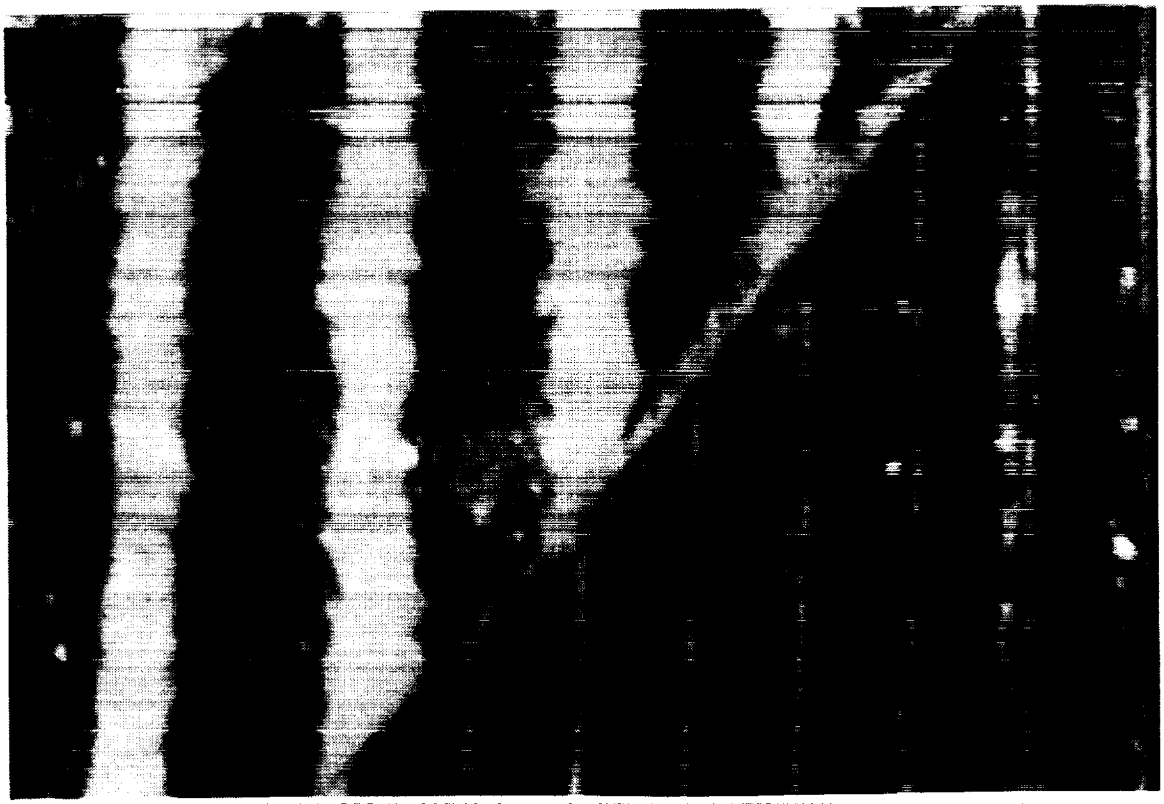


Figure 7. Silica cell cover surface at 200X magnification.



NOTES: - BARE "CELL" UPPER LEFT, COVERED "CELL" LOWER RIGHT
- WHITE SIMULATED "GRIDLINES" ARE ON 0.016 INCH CENTERS

Figure 8. Photograph of sol-gel glass prismatic cell cover over a linear pattern simulating solar cell gridlines.

illustrate the excellent replication accuracy of the sol-gel technique, a photograph of the surface of the polystyrene mold is shown in Figure 6. Groove marks, created during fabrication of the master prism cover tool and transmitted to the polystyrene mold, are clearly visible. As seen in Figure 7, the same machining grooves present in the polystyrene mold were translated through the sol-gel processing and are also visible in the finished silica part.

Since the molds were made from an existing master tool, which was not designed to account for sol-gel processing shrinkage, photovoltaic cells with the proper front metallization pattern were not readily available. Thus a direct measure of current gain achieved by using the sol-gel prism cover could not be obtained at that time. In an effort to simulate the visible effects of the prism cover, a finished glass prismatic cover was placed over a pattern of alternating white and black parallel lines (simulating the gridlines on a concentrator cell). The results of this experiment are shown in Figure 8. The glass prism cover performed as expected, optically eliminating the white "gridlines" from view.

While the work in this area was limited to a single Phase I SBIR contract, a number of significant results were achieved under this effort. The replication capabilities of the sol-gel casting process were clearly demonstrated and two all-glass prismatic cell covers were made. While the progress was notable, a number of other issues such as final part thickness, sol-gel processing time, large-scale manufacturability, etc. will need to be addressed in future efforts.

SILICONE PRISMATIC CELL COVERS

As mentioned previously, prismatic cell covers have been used extensively in ENTECH's commercially-available terrestrial concentrator systems. The ENTECH concentrator is a linear design that uses a silicon concentrator cell approximately 1.5 by 3.5 inches in size. The cell operates at a nominal concentration of 22 suns and has about 25% front metallization grid coverage. Until recently, the silicone prism covers were made by a labor-intensive cast-and-cure process. While this process is very repeatable and produces high quality covers, it does not readily lend itself to a large quantity, low cost manufacturing approach.

During the past year, under the U.S. Department of Energy's Photovoltaic Manufacturing Technology (PVMaT) Initiative, ENTECH and 3M have successfully demonstrated a continuous production process for making silicone prismatic cell cover "tape". A photograph of a 200 ft. roll of the new prism cover "tape" is shown in Figure 9. This new product is made by a proprietary 3M process and results in excellent optical quality at a low manufacturing cost. The optical quality of the cell covers produced by this process is better than that of the covers made by the previous cast-and-cure process. The new "tape" not only reduces the cost of the prismatic cover by an order of magnitude, but also makes its application to the solar cell much easier and quicker. The "tape" comes with a relatively stiff transparent liner on the prismatic surface. The semi-rigid transparent liner supports the flexible silicone cover during alignment and during the rapid thermal curing of the adhesive layer between cover and cell. A cross-section of the new prism cover "tape," after it has been applied to a photovoltaic cell, is shown in Figure 10.

While this new process applies primarily to the terrestrial photovoltaic market, it has been discussed here because of the significant potential it offers for space applications. The process could not only be used to make prismatic covers for space photovoltaic devices, but it also could be applied to the fabrication of linear Fresnel lenses. The prismatic cell cover pattern on the current roll-to-roll process could easily be changed to a linear Fresnel lens concentrator pattern. This could significantly affect the ease of manufacturability, and cost, of future refractive concentrator optics. The development of the line-focus refractive concentrator is discussed further in the next section.

LINE-FOCUS FRESNEL LENS CONCENTRATORS

The mini-dome Fresnel lens concentrator system offers a number of distinct performance advantages over state-of-the-art planar arrays (ref. 8). However, these performance gains come with the added requirement of two-axis tracking for the point-focus concentrator system. While the performance improvements of advanced space concentrator systems are substantial at the array level, the ultimate benefit, and eventual use of such systems, will be dependent upon "system" implications and performance. This means that the array must not be viewed as a separate entity, but as an integral part of the spacecraft. Under this viewpoint, tracking requirements, stowability, structural dynamics, etc. become as important as the panel efficiency, specific power and radiation hardness of the array.

Keeping these "system" aspects in mind, there may be a number of space missions where single-axis tracking requirements have a distinct benefit over double-axis tracking. Thus, NASA Lewis has decided to initiate a small program to investigate linear refractive concentrator systems for use in space. Under a SBIR Phase I contract, ENTECH will develop a line-focus Fresnel lens concentrator element. The line-focus lens will be made in a flat form, and then mechanically contoured to the desired aspheric shape. A sketch of the linear concentrator element is shown in Figure 11. The prototype elements will be fabricated with various rim angles and focal plane irradiance profiles to allow for the experimental verification of various lens design parameters.

While the program has just started, there already seem to be a number of inherent advantages to the linear concentrator element. Besides the reduction in tracking requirements to a single axis, linear lenses seem to offer substantial benefits in ease of manufacturability and cost over refractive point-focus elements. Indeed, the new continuous silicone prism cover "tape" process, discussed above, could be directly applicable to linear Fresnel lens production. These benefits still need to be quantified, as do the effects of reduced concentration ratio and increased cell area on system performance and cost. This program will address these issues and, in doing so, try to determine the usefulness of linear Fresnel lens concentrator systems for various space missions.

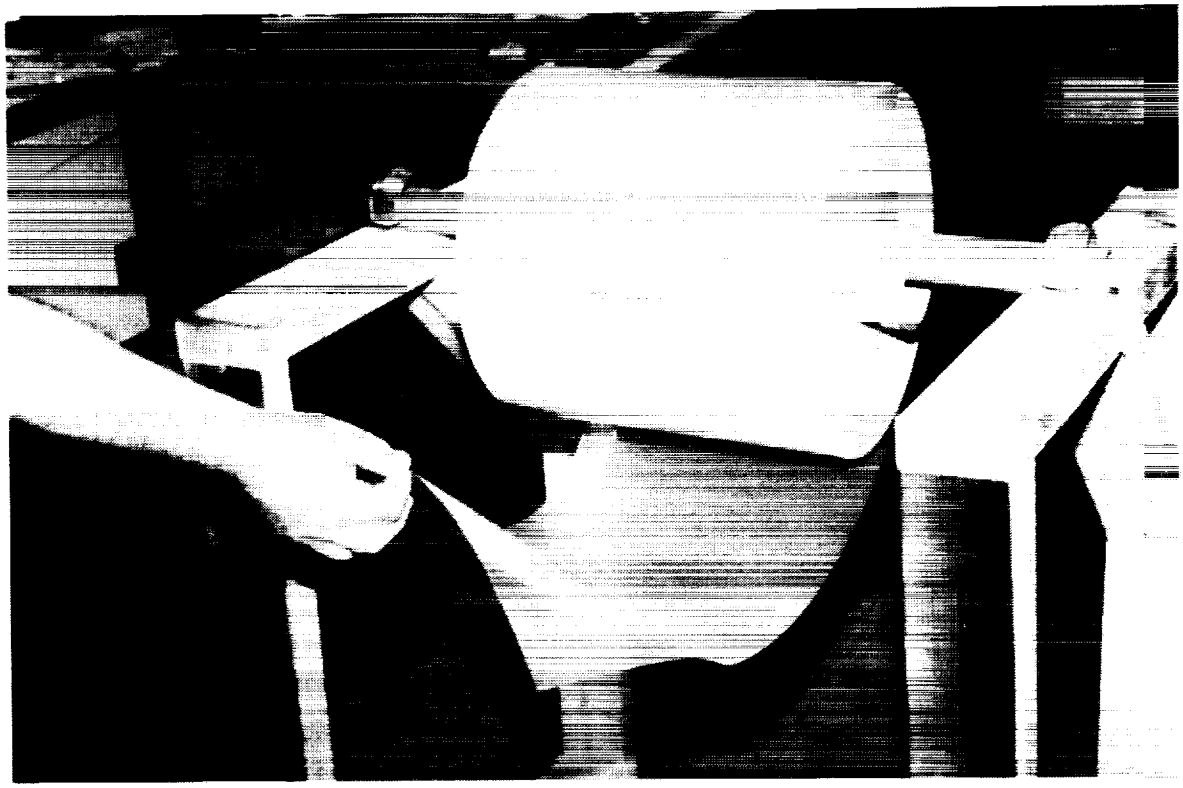


Figure 9. Photograph of 200 ft. roll of prismatic cell cover "tape" developed under PVMaT Program.

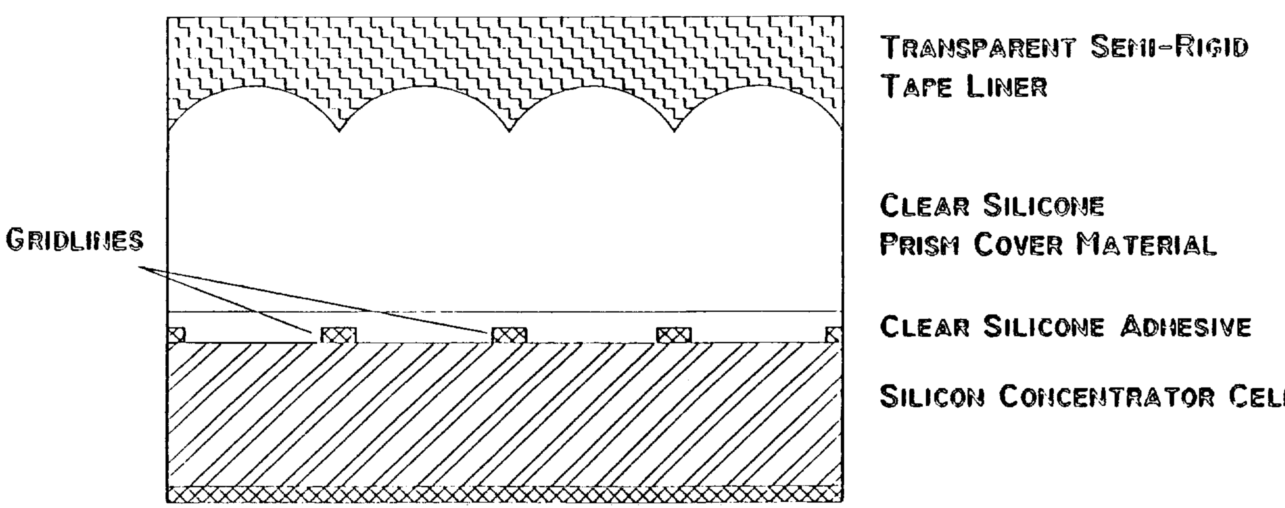


Figure 10. Schematic of new prismatic cell cover "tape" material applied to a terrestrial silicon concentrator cell.

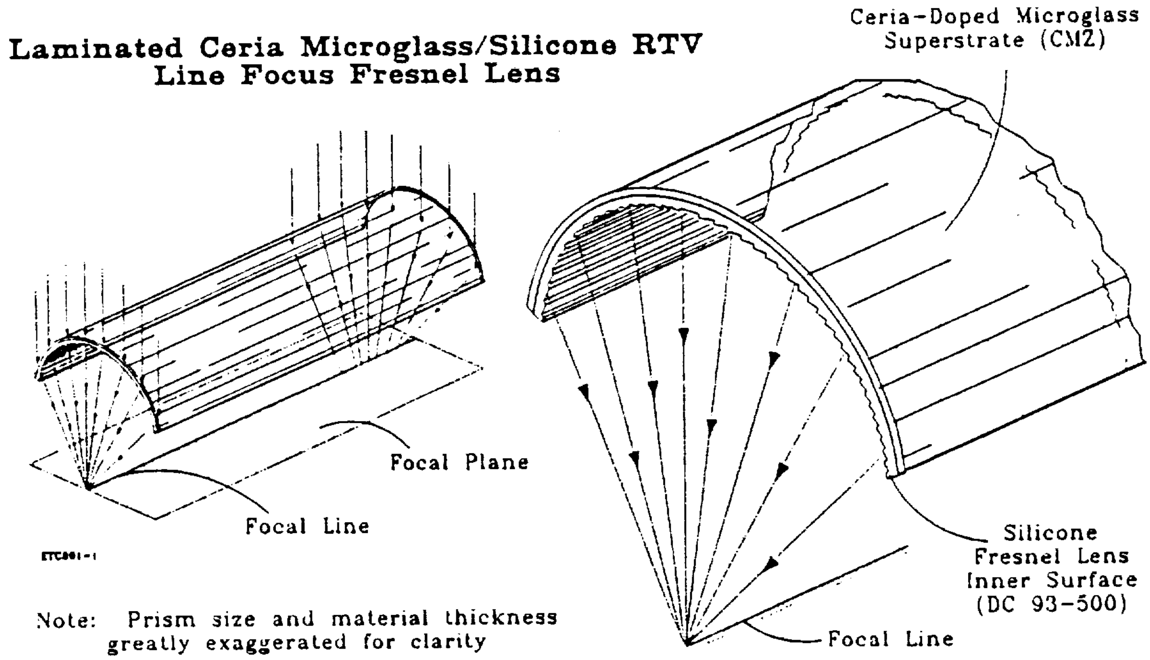


Figure 11. Proposed Linear Fresnel Lens Photovoltaic Concentrator Element for Space

SUMMARY

A number of recent achievements have been made in the development of space-based refractive concentrator systems and components. The mini-dome Fresnel lens concentrator program continues to grow, currently emphasizing the areas of manufacturability and environmental durability. The program is now awaiting critical flight data from a variety of space experiments. All-glass prismatic cell covers have been made, demonstrating the ability of the sol-gel process to fabricate the intricate designs necessary for good prismatic cell cover performance. Advances have been made in the manufacturability of silicone prism covers for terrestrial photovoltaic concentrator systems under the Department of Energy's PVMat Initiative. This new roll-to-roll prism cover "tape" process may have direct applicability to a variety of space refractive concentrator systems, significantly influencing the manufacturability and cost of these advanced systems. As a supplement to the current refractive concentrator program, work has also started on the development of a line-focus Fresnel lens concentrator element. These developments, along with similar improvements in the efficiency photovoltaic concentrator cells, could have a dramatic impact on the performance of future spacecraft power systems.

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